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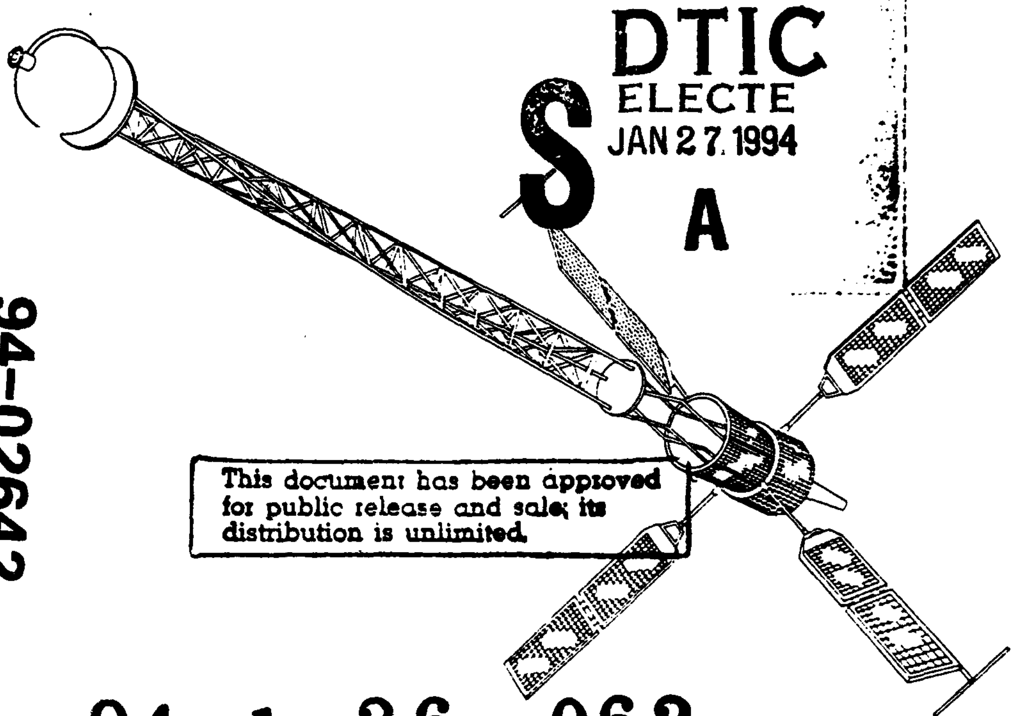
Nonlinear Dynamics of Deployable and Maneuverable Space Structures

University Research Initiative
AFOSR Grant/Contract No. AFOSR-90-0211

Professors F.C. Moon and J.F. Abel
204 Upson Hall, Cornell University, Ithaca, NY 14853

FINAL REPORT
April 1990 - September 1993



Nonlinear Dynamics and Control of Flexible Structures

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13. ABSTRACT The research goals of this URI efforts are: 1) to study the effects of nonlinearities on the dynamics of deployable and maneuverable structures, including the possibility of chaotic or transient dynamics, 2) to design experiments to study slewing transients of flexible structures both to test the analytical models and to explore for possible unmodelled dynamic effects, 3) to study the motion of unfolding of deployable structures, and 4) to advance computational capability for the simulation of dynamic controlled deployment and maneuver of large flexible structures. The accomplishments include: 1) developed a soliton deplyment straegy for folded panel space structures, 2) showed spatially complex and chaotic solutions of a twisted elastica, 3) established evidence for transition from soliton to chaotic transient dynamics, 4) developed a robust cable controlled flexible robot arm structure, 5) completed the structural modelling, attribute assignment and visulization capabilities of an interactive graphic 3-D system for dynamic and static structural analysis, and 6) completed work on coarse-grained parallel processing for nonlinear structural dynamics by developing new explicit and implicit analysis and automatic domain partitioning algorithm for load balancing among processors.

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URI II

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OVERVIEW

The research goals of this project have been:

I) To study the effects of nonlinearities on the dynamics of deployable and maneuverable structures, including the possibility of chaotic or transient dynamics.

II) To design experiments to study slewing transients of flexible structures both to test the anlytical models and to explore for possible unmodelled dynamic effects.

III) To study the motion of unfolding or deployable structures both experimentally and analytically using one or more prototype systems. The goals are to derive methodologies for formulation of the governing nonlinear systems of equations and to test solutions for specific systems.

IV) To advance practical numerical simulation of the dynamic controlled deployment and maneuver of large flexible structures by including geometrically exact large rotation/displacement effects and by imporving the robustness and efficiency of solution methods for the highly nonlinear effects.

The hallmark of the research has been a balance among theory, experiments, and numerical simulation as well as a strong interaction among these components.

SUMMARY OF ACCOMPLISHMENTS

1. Developed a soliton deployment strategy for folded panel space structures.

2. Showed spatially complex and chaotic solutions of a twisted elastica.

3. Studied the impact dynamics of a multi-bay nonlinear elastic structure. Established evidence for transition from soliton to chaotic transient dynamics.

4. Studied the slewing transients of a cable controlled flexible robot arm structure.

5. Made significant progress in the development of innovative object-oriented 3-D nonlinear simulation tools for deployable and meneuverable space structures. Continued to employ and improve basic nonlinear analysis capabilites for the

controlled and uncontrolled dynamics of structures which were developed in earlier research sponsored by AFOSR (URI I) and others (NCEER, NASA LeRC).

6. Completed the structural modelling, attribute assignment, and visualization capabilities of our interactive graphic 3-D system for dynamic and static structural analysis.

7. Completed work on coarse-grained parallel processing for nonlinear structural dynamics by developing explicit and implicit anlalysis capabilities as well as a new automatic domain partitioning algorithm for load-balancing among processors.

PROJECT PARTICIPANTS

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Christopher White, Civil and Environmental Engineering, Graduate Research Assistant (Spring and Summer 1993 only). PhD expected May 1995.

BOOKS, PAPERS, PRESENTATIONS AND THESES

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RESEARCH ABSTRACTS

Following are abstracts of each of the subprojects active at the end of the third year of the parent project. The six topics encompassed are:

I. Soliton Deployment Dynamics for Folded Panel Space Structures
II. Impact Dynamics of Nonlinear Elastica Structures: Solitons and Spatial Chaos
III. Spatially Chaotic Deformation of the Elastica
IV. Development of Analytical Capabilities for Realistic and Efficient Simulations of 3-D Space Structures
V. Interactive Modelling of 3-D Structures
VI. Parallel Nonlinear Dynamic Analysis

Research Abstracts

I. Soliton Deployment Dynamics of Folded Panel Space Structures

A simplified one-dimensional model was adopted to study the problem of the dynamics of deployable structures. The model provides a nonlinear potential energy vs. displacement function for individual sections that form a large structure such as a solar panel. The model assumes that the structure is clamped at one end, and free at the other (Figure 1).

It was discovered that work done with nonlinear lattices, specifically molecular systems, was very similar to the problem being studied.

Numerical simulations were conducted on both the original system and one of the molecular systems as well. It was possible to numerically duplicate work that had been done with solitons and molecular systems. With this as a starting point, the original system was tested under a variety of initial conditions to see if solitary waves could be generated within it. Solitons were generated in the original system, and were found to facilitate the deployment process.

In addition to the one-dimensional models simulated, recommendations are provided to extend the simulations to an umbrella-like structure with periodic boundary conditions.

II. Impact Dynamics of Nonlinear Elastic Structures: Solitons and Spatial Chaos

Evidence for transition from soliton to chaotic motion in a nonlinear elastic periodic structures has been obtained for both impact and periodic loading. Experiments and numerical simulation are used to show how solitary wave dynamics in a coupled cell system with a finite number of cells can evolve into a complex spatial pattern with chaos-like dynamics. The experiment consists of eight elastic oscillators coupled with buckling sensitive elastica. This structure is analogous to those found in space structures, ship and aircraft structures (see Figure 2).

Numerical prediction of dynamic deformation of imperfection sensitive structures such as plates, shells, and arches have traditionally been poor predictors of actual motion, especially under transient loads. In this study we provide evidence for the inherent unpredictability of calculations of such nonlinear structural dynamics. Both numerical and

experimental measurements show how spatially coherent motions such as solitary waves break up into chaotic motions, extremely sensitive to initial conditions.

III. Spatially Chaotic Deformation of the Elastica

Elastica-based deployable structures have been designed for space antenna in both the United States and Japan (Figure 3). We investigate the existence of spatially chaotic deformations in an elastica and the analogous motions of a free spinning rigid body, an extension of the problem originally examined by Kirchhoff. It is shown that a spatially periodic variation in cross sectional area of the elastica results in spatially complex deformation patterns. The governing equations for the elastica were numerically integrated and Poincaré maps were created for a number of different initial conditions. In addition, three dimensional computer images of the twisted elastica were generated to illustrate periodic, quasi-periodic, and stochastic deformation patterns in space. These pictures clearly show the existence of spatially chaotic deformations with stunning complexity. This finding is relevent to a wide variety of fields in which coiled structures are important, from the modeling of DNA chains to video and audio tape dynamics to the design of deployable space structures (Figures 4,5).

IV. Development of Analytical Capabilities for Realistic and Efficient Simulations of 3-D Space Structures

In this project we seek to develop numerical tools for simulating large deformation nonlinear dynamics of space structures. We focus in particular on structures made of rods. Problems of interest include activity controlled slewing, as well as deployment and stowage. We hope to achieve realistic, accurate, and robust simulations with relatively coarse spatial and temporal discretization, by employing geometrically exact, material frame indifferent formulations [A. Cardona and M. Geradin (1988)] and unconditionally stable, momentum-preserving, implicit time-integration schemes [J. C. Simo et al., (1992)]. We follow A. Cardona, M. Geradin, and D. B. Doan (1991) in modeling constraints as special elements, and make use of sophisticated linear and nonlinear system solvers to reduce the need for expensive matrix factorizations.

All these methods and techniques are as complex to implement as the problems they address are challenging, and require a significant amount of experimentation and fine-tuning. In order to support their integration, a new object-oriented nonlinear dynamics analysis platform (henceforth referred to as ONDAP) is being developed, which emphasize modularity, clarity, flexibility, and reusability. It is organized in three sparsely interfacing modules responsible, respectively, for the finite element model (configuration updates, force/stiffness recovery), the analysis (assembly and solution of nonlinear system of equations), and the input/output.

The design of ONDAP re-addresses central procedures of the method of finite elements as object relations and rules of production. It makes the essence of the method obvious through innovative object classes, such as element-fields, element nodes, and nodal-variables, instead of hiding it in page-long definitions of stiffness matrix entries. Verifying the correctness of a new formulation's implementation is uncommonly easy in ONDAP, due to the element mechanics being expressed in terms of algebra of vector fields. ONDAP encourages experimentation by turning disjoint element implementations into parameterized options (e.g., element topology, order of field interpolation, rule and order of element quadrature, etc.). Finally, options which are mathematically, if not conceptually, independent are identified and assigned to different object classes, to

minimize duplication and maximize reusability of code. Overall ONDAP is designed to be modular, readable, reliable, and easy to expand.

Common operations in ONDAP have been standardized and centralized, in order to preserve reliability. Most object data structures have been defined, although some are not finalized. Functionality for linear elastic material model, prismatic I-beam structural members, and Lagrange interpolation on a Cartesian product topology have been implemented. An extensive library of vector and tensor functions has been created, with special emphasis on rotations and derivatives thereof. An interface with BASYS (the in-house pre- and post-processor -- see "Interactive Modelling of 3-D Structures" below) has been designed and is almost completely coded. Functionality that maps the BASYS description into ONDAP's internal representation has been designed and partially implemented.

The tasks that must be completed before a meaningful problem can be analyzed fall into two categories: general, having to do with the overall organization of ONDAP, and specific. The general tasks are the design and implementation of operations for degree of freedom numbering, updating of configuration, force and/or stiffness recovery, and implicit time integration. Specific tasks include implementation of element mechanics for rods as in Simo and Vu-Quoc (1991), Gauss quadrature on Cartesian product topologies, value and gradient calculation for position vector and rotation pseudo-vector variables, a simple line search algorithm, and skyline matrix functionality (initialization, assembly, left-multiplication into vector, factorization, forward- and back-substitution.

Once ONDAP is operation and stable, the implementation of constraint finite elements for realistic modeling of joints, and of advanced nonlinear system solvers for increased efficiency can be undertaken.

V. Interactive Modelling of 3-D Structures

This aspect of research involves enhancement of the three-dimensional structural modelling software BASYS [Srivastav (1991)]. A radial-edge topological database is used by BASYS to represent frame or truss structures comprised of elements having zero, one, or two dimensions (joint, line, and surface finite elements.) In the past, BASYS required that structural models be created and all attributes be assigned using a separate program, such as CU-PREPF [McGuire et al. (1989)]. As a result of this research and development in the third year of the project, tools are now in place which permit BASYS to be used for the entire model-building process.

Models are generated in BASYS by copying or extruding simple three-dimensional objects to eventually generate the complete structure. The simple objects are created using the Grid generator, or by repeated use of the Add operators (Add vertex, Add edge, Add face.) In BASYS, copying is a two-stage operation where the entities to be copied are first specified and stored in a temporary list, which is in turn operated upon by the copy algorithm selected by the user. Available copying algorithms include copying along a line, along a circular arc, along a radius, and mirror imaging about either a line (for two-dimensional problems) or a plane. Editing functions such as Delete, Split Edge, and Move are also available. Move operations are particularly hard to implement, even with element geometry being an attribute of the structural topology, as in BASYS. Sophisticated checks are necessary to ensure that (1) edges and surfaces will not penetrate existing surfaces, (2) overlapping elements (vertex-vertex, edge-edge, and face-face) will not be generated and pass into the database unknown to the user, and (3) surfaces do not lose their planar geometry as a result of a move request.

Attribute assignment involves two stages. First an attribute is defined and stored, then the components which inherit it are specified. For most attribute classes, BASYS employs a table and pointer-to-table paradigm which is described below. Special operators are included to accommodate orientation-dependent attributes such as orthotropic material, principal axes of bending for beam elements, and follower-type joint or member loads. Finally, pre-assigned attributes are conveniently propagated by the copy operators.

The table-and-pointer-to-table scheme is chosen because it minimizes storage requirements and facilitates modifications. It is typified by its application to material attributes. Typically, structures are constructed of several different materials. Each material type will have a table of its properties stored as an attribute of the model. Also stored with the material properties is a user-defined table name: subsequent references to the material table are made through this name. The attribute assignment procedure begins with the user specifying which of the stored tables is "active". As the table is assigned to a structural component, the component sets its material properties pointer to point to the currently "active" table.

Often, the user desires to know the coordinates of a specified vertex, the distance between vertices, or the coordinates and attribute data associated with a structural component such as an edge or surface element. An Inquiry menu page has been implemented to satisfy such queries, with the associated information appearing in a special Inquiry message box which is updated after each entity pick.

A mechanism has been provided which allows the user to define logical groups of structural elements for the purposes of assigning attributes, requesting analysis output, enhancing graphical displays, or for copying, moving, deleting, etc. Each group is referenced through a name and is displayed with a distinct color, both of which are specified by the user when the group is created. Extensions of this grouping feature will be made to post-processing features as time permits.

Active control is an important feature of many space structures. Anticipating the need to study actively-controlled systems, rudimentary features for them have been incorporated into the current version of BASYS. Active control systems considered in this research can be defined in terms of non-distributed sensors and control actuators. Sensors which monitor any combination of state variables in any orthogonal set of directions, fixed or follower, can be specified. Control actuators may be defined which are of the active mass, active tendon, or active strut type. Currently, BASYS interfaces with analysis software such as ABREAST and MATLAB through formatted ASCII files.

The work associated with this aspect of the research is rapidly nearing completion. The BASYS software is already being used to model complicated space structures, buildings, and other structures which require surface elements. An example is shown in Figure 6. The next logical phase of software development involves incorporating the properties of structural connections, especially connections between two edge elements or between edge and surface elements. Incremental improvements in postprocessing capabilities will be undertaken as time permits.

VI. Parallel Nonlinear Dynamic Analysis

The principal objective of this portion of the research, only partially supported under this grant, is to investigate, develop, and demonstrate coarse-grained parallel-processing strategies for nonlinear dynamics simulations. The parallel-processing

strategies addressed include numerical algorithms for parallel nonlinear solutions and techniques to effect load balancing among processors. The parallel environment employed is a distributed-memory, coarse-grained one consisting of networked workstations. Both parallel explicit and implicit time integration methods have been implemented for transient nonlinear nonlinear solutions. In the current year, automatic domain partitioning techniques have been investigated for load-balancing among processors, and a new version of Simon's spectral approach [Simon (1991)] has been developed, called the recursive spectral two-way (RST) algorithm. Advance computing environments, data structures, and interactive computer graphics all contribute to an integrated parallel finite element analysis system to facilitate more efficient and powerful dynamics simulations.

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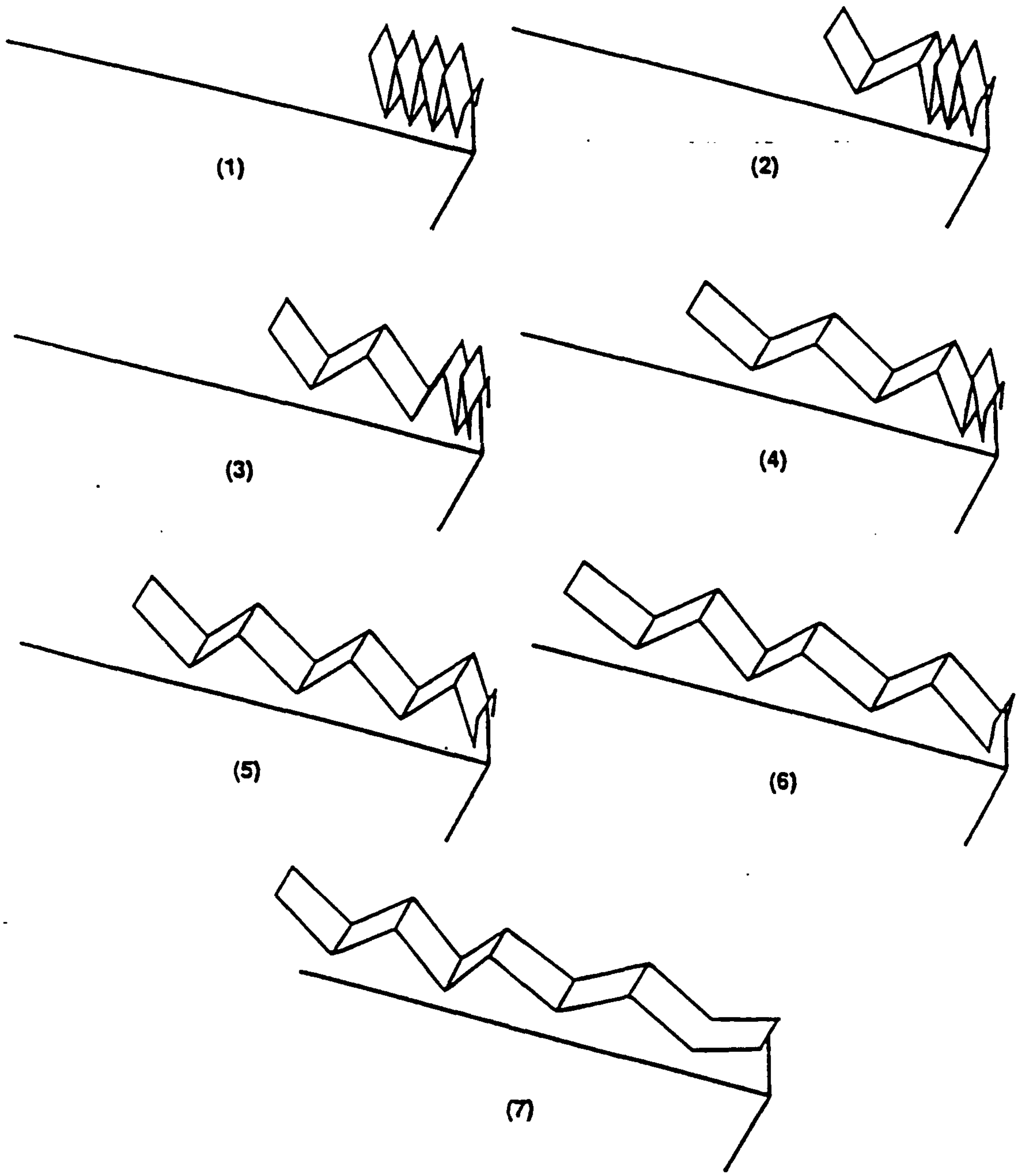
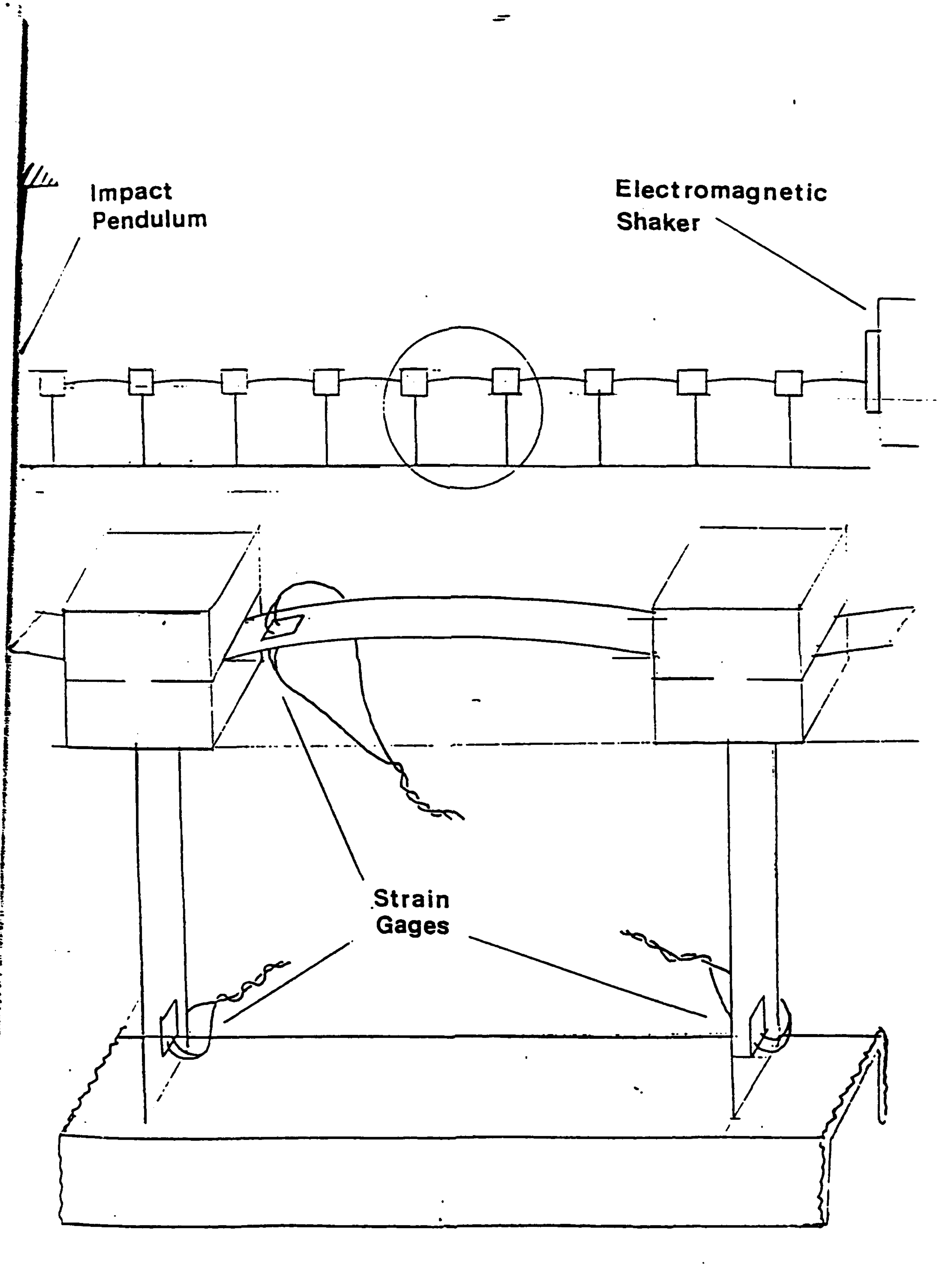


Figure 1.



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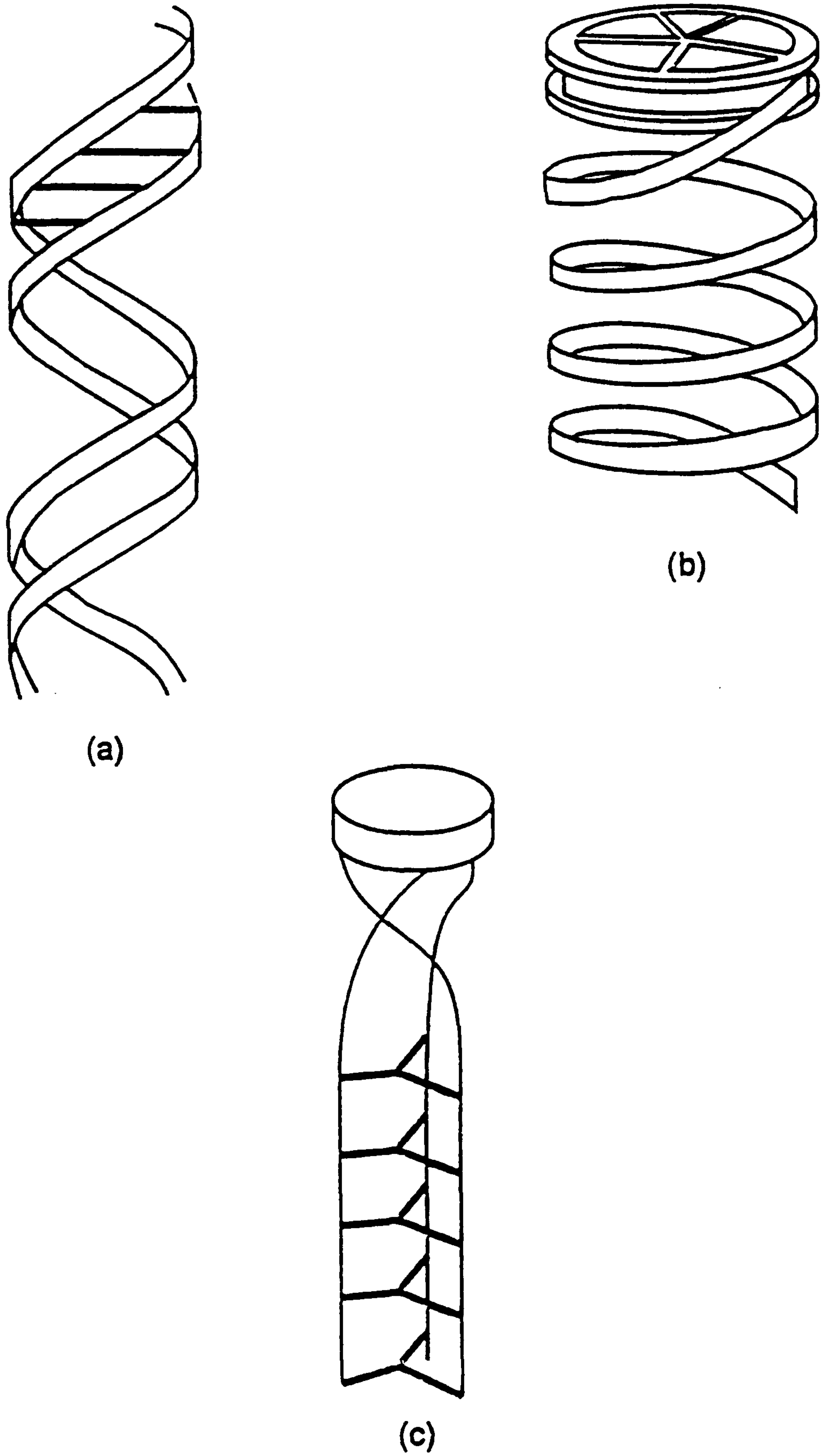

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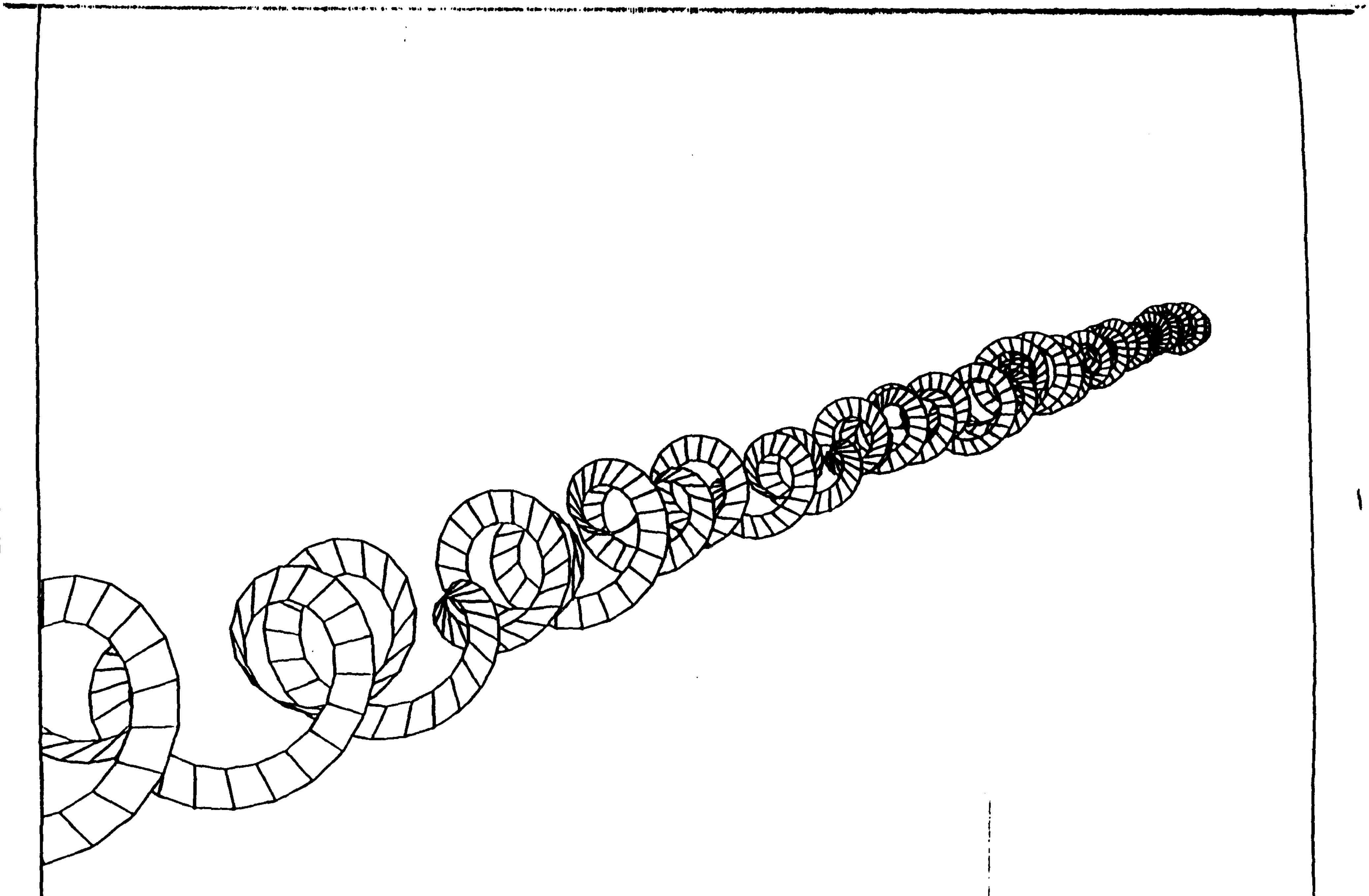

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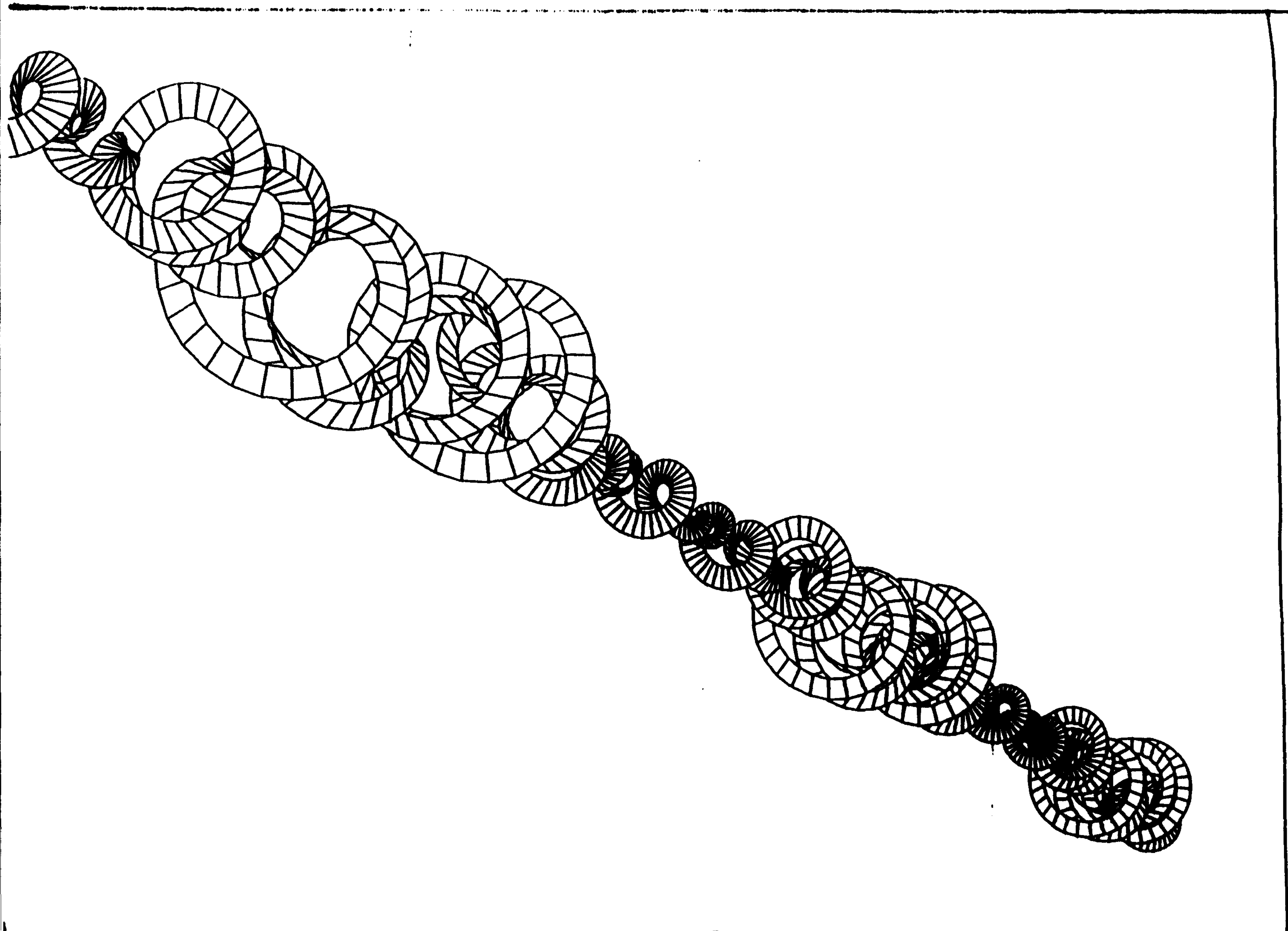

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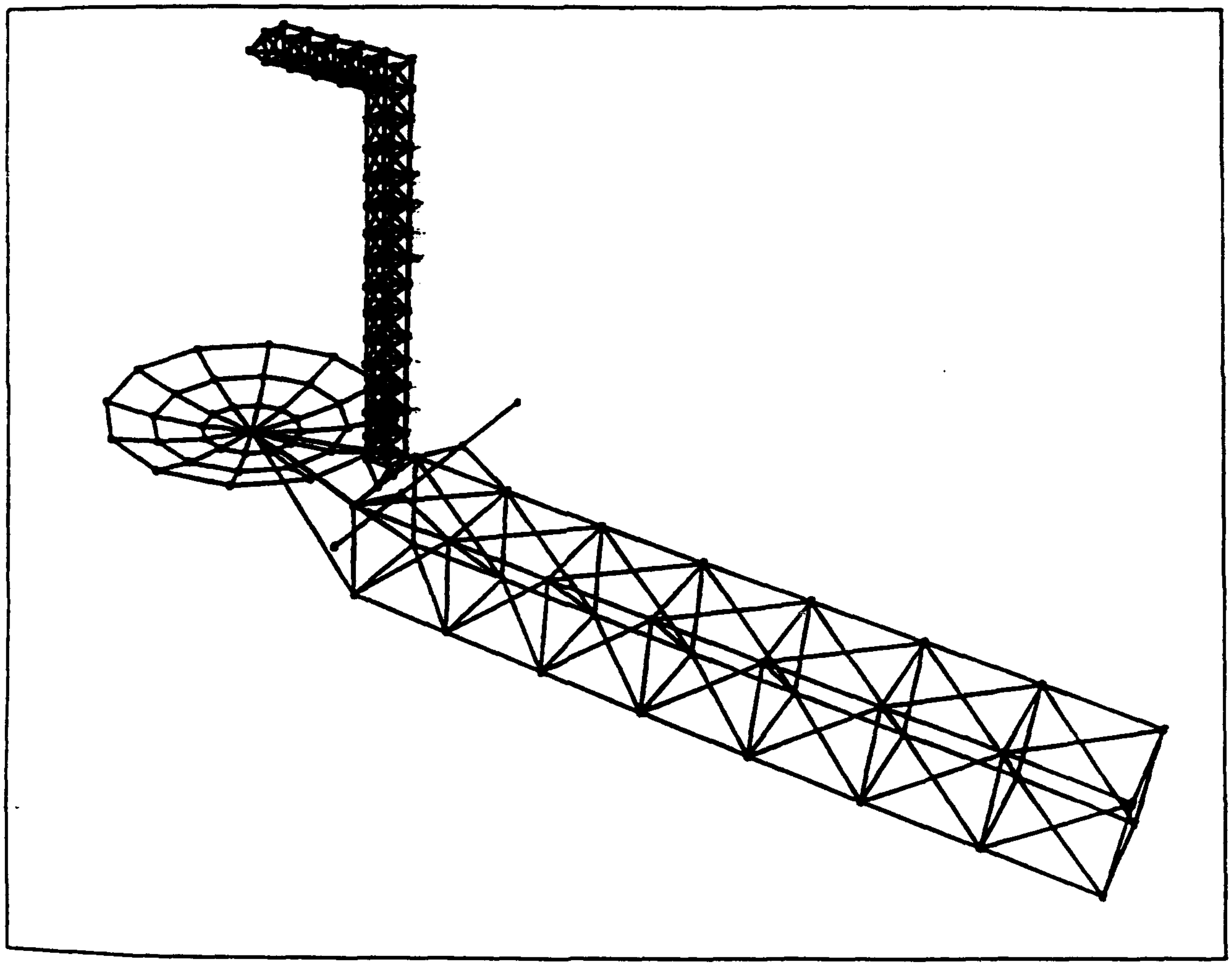

Figure 6.